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A New Limit on the neutrinoless $\beta\beta$ -decay of ^{130}Te

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We report the present results of CUORICINO a cryogenic experiment on neutrinoless double beta decay (DBD) of ^{130}Te consisting of an array of 62 crystals of TeO_2 with a total active mass of 40.7 kg. The array is framed inside of a dilution refrigerator, heavily shielded against environmental radioactivity and high-energy neutrons, and operated at a temperature of ∼8 mK in the Gran Sasso Underground Laboratory. Temperature pulses induced by particle interacting in the crystals are recorded and measured by means of Neutron Transmutation Doped thermistors. The gain of each bolometer is stabilized with voltage pulses developed by a high stability pulse generator across heater resistors put in thermal contact with the absorber. The calibration is performed by means of two thoriated wires routinely inserted in the set-up. No evidence for a peak indicating neutrinoless DBD of ^{130}Te is detected and a 90 % C.L. lower limit of 1.8×10^{24} years is set for the lifetime of this process. Taking largely into account the uncertainties in the theoretical values of nuclear matrix elements, this implies an upper boud on the effective mass of the electron neutrino ranging from 0.2 to 1.1 eV. This sensitivity is similar to those of the ^{76}Ge experiments.

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Great interest was stimulated in recent years in neutrinoless double beta decay (DBD) as a consequence of the observation of neutrino oscillations [1, 2, 3, 4, 5, 6], proving that the differences between the squares of the neutrino mass eigenvalues is different from zero. This indicates that the mass m_ν of at least one neutrino is finite, but does not allow the determination of its absolute value.

The value of the sum of the masses of the neutrinos of the three flavors has been constrained to values from 0.7 to 1.7 eV from the WMAP full sky microwave map together with the survey of the 2dF galaxy redshift [7, 8, 9, 10, 11]. A claim for a non zero value of 0.64 eV has also been proposed [12]. These values are more constraining than upper limits of 2.2 eV for m_ν obtained so far in experiments on single beta decay, but they are strongly model dependent and therefore less robust than laboratory measurements. Limits of ∼0.2 eV are expected in KATRIN experiment [13]. If neutrinos are Majorana particles more stringent constraints, or a positive value for the effective neutrino mass, can be obtained by neutrinoless DBD. In this lepton violating process, a nucleus (A,Z) decays into (A,Z+2) with the emission of two electrons and no neutrino. This leads to a peak in the sum energy spectrum of the two electrons. The decay rate of this process would be proportional to the square of the effective neutrino mass $|\langle m_\nu\rangle|$, which can be expressed in terms of the elements of the neutrino mixing matrix as follows:

$$|\langle m_\nu\rangle| \equiv ||U^L_{e1}|^2 m_1 + |U^L_{e2}|^2 m_2 e^{i\phi_2} + |U^L_{e3}|^2 m_3 e^{i\phi_3}|, \quad (1)$$

where $e^{i\phi_2}$ and $e^{i\phi_3}$ are the Majorana CP–phases (± 1 for CP conservation), $m_{1,2,3}$ are the Majorana neutrino mass eigenvalues and U^L_{ej} are the coefficients of the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) neutrino mixing matrix, determined from neutrino oscillation data. Recent global analyses of all oscillation experiments [14, 15, 16, 17, 18, 19, 20, 21, 22, 23] yield on average:

$$|\langle m_\nu\rangle| = |(0.70 \pm 0.03)m_1 + (0.30 \pm 0.03)m_2 e^{i\phi_2} + \\ +(< 0.05)m_3 e^{i\phi_3}| \quad (2)$$

It should be stressed that neutrino oscillation experiments can only yield neutrino mass eigenvalue differences

squared, and imply two possible patterns, or hierarchies, the normal: $m_1 \approx m_2 << m_3$, and the inverted hierarchy: $m_1 << m_2 \approx m_3$. The mass parameter measured in solar oscillation experiments, δ_{solar}, is $m_2^2 – m_1^2$ in the normal hierarchy case and $m_3^2 – m_2^2$ in the inverted case. That measured in atmospheric neutrino experiments, δ_{atm}, is then approximately $m_3^2 – m_1^2$ in both cases. If we neglect U^L_{e3}, and also note that experimentally, $\delta_{solar} << \delta_{atm}$, two useful approximate expressions for $|\langle m_\nu \rangle|$ result:

$$|\langle m_\nu \rangle| = m_1 |0.70 + 0.3 e^{i\phi_2}(1 + \delta^2_{solar}/m_1^2)| \quad (3)$$

for normal hierarchy and

$$|\langle m_\nu \rangle| = \sqrt{m_1^2 + \delta^2_{atm}} |0.70 e^{i\phi_2} + 0.3 e^{i\phi_3}| \quad (4)$$

for inverted hierarchy. If one uses the value, $\delta_{atm} = 2 \times 10^{-3}$, equation (4) implies that $|\langle m_\nu \rangle|$ could have a minimum value as large as 0.045 eV, which implies a minimum sensitivity acceptable for next generation experiments on neutrinoless DBD.

One should note that the rate for neutrinoless DBD is proportional also to the square of the nuclear matrix elements whose calculations are still quite uncertain. As a consequence it is imperative to search neutrinoless DBD in different nuclei. This is also true because a peak attributed to this process could in principle be mimicked by a radioactive line. Only the discovery of peaks at the different energies expected for neutrinoless DBD in two or more candidate nuclei would definitely prove the existence of this process. No evidence for neutrinoless DBD has been reported so far [24, 25, 26, 27], with the exception of the claimed discovery of the decay of ^{76}Ge reported by a subset of the Heidelberg-Moscow collaboration [28]. This claim has been contested by various authors [14, 29, 30] and also by other members of the same Heidelberg-Moscow Collaboration [31]. A new analysis in favor of the previous claim has however been published recently [32, 33].

Here we report new results on the neutrinoless DBD of ^{130}Te from the CUORICINO experiment operating in the Gran Sasso Underground Laboratory at a depth of about 3500 m.w.e.[34]. This search, like the previous ones performed in the same laboratory, is carried out with the cryogenic technique suggested for the first time twenty years ago for searches for rare events [35]. Cryogenic thermal detectors [36, 37] are made by diamagnetic and dielectric crystals kept at low temperature, where their heat capacity is proportional to the cube of the temperature itself. As a consequence, their heat capacity can become so small that even the tiny energy delivered to this "absorber" by particle interaction , can be detected and measured by means of a suitable thermal sensor. Since the only requirement for these absorbers is that they have reasonable thermal and mechanical properties, cryogenic detectors offer a wide choice of candidate nuclei for searches on DBD. The ^{130}Te nucleus is an excellent candidate due to its high transition energy (2528.8 ± 1.3 keV) [38], and especially to the unusually large isotopic abundance (33.8%) [39] which makes the need for enrichment less important. A preliminary report on the first part of this experiment was published earlier [40].

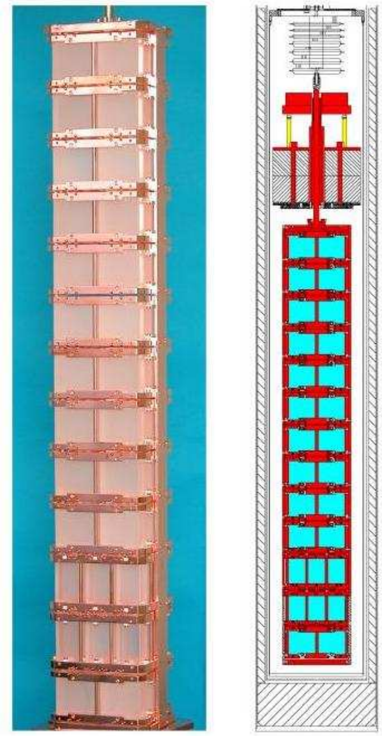

FIG. 1: Scheme of CUORICINO.

CUORICINO (Fig. 1) is a tower of 13 planes containing 62 crystals of TeO_2 ; 44 of them are cubes of 5 cm on a side while the dimensions of the others are 3×3×6 cm^3 . All crystals are made with natural paratellurite, apart from two 3×3×6 cm^3 crystals, which are enriched in ^{128}Te and two others of the same size enriched in ^{130}Te , with isotopic abundance of 82.3 % and 75 %, respectively. The total mass of TeO_2 in CUORICINO is 40.7 kg, the largest by more than an order of magnitude than any cryogenic detector. More details on the preparation of the crystals and on the mechanical structure of the array is reported elsewhere [40].

In order to shield against the radioactive contaminants from the materials of the refrigerator, a 10 cm layer of Roman lead, with ^{210}Pb activity of <4 mBq kg^{-1} [41], is inserted inside the cryostat immediately above the CUORICINO tower. A 1.2 cm lateral layer of the same lead is framed around the array to reduce the activity of the thermal shields. The cryostat is externally shielded by two layers of Lead of 10 cm minimal thickness. While the outer is made by common Lead, the inner one has a ^{210}Pb activity of (16 ± 4) Bq kg^{-1}. An additional layer of 2 cm is provided by the electrolitic Copper of the thermal shields. The background due to environmental neutrons is reduced by a layer of Borated Polyethylene

of 10 cm minimum thickness. The refrigerator operates inside a Plexiglass anti-radon box flushed with clean N_2, and inside a Faraday cage to reduce electromagnetic interference.

Thermal pulses are recorded by means of Neutron Transmutation Doped (NTD) Ge thermistors thermally coupled to each crystal. Stabilization is performed by means of voltage pulses developed across heater resistors attached to each bolometer. The voltage pulses are generated by high stability pulse generators, designed and developed on purpose [42]. A tagging of these stabilizing signals is made by the acquisition system. The detector baseline is stabilized with a dedicated circuit with a precision of better than about 0.5 KeV/day on the average [43] between the successive refilling of liquid helium of the main reservoir.

The front-end electronics for all the 3×3×6 cm^3 and for 20 of the 5×5×5 cm^3 detectors are mantained at room temperature. In the so called *cold electronics* , applied to the remaining 24 crystals, the preamplifier is located in a box at ∼100 K near the detector to reduce the noise due to microphonics [44], which would be very dangerous when searching for WIMPS. More details on read-out electronics and DAQ are reported in [40].

CUORICINO is operated at a temperature of ∼8 mK with a spread of ∼1 mK. A routine energy calibration is performed before and after each sub-run, which lasts about two weeks, by exposing the array to two thoriated tungsten wires inserted in immediate contact with the refrigerator. All data, in which the average difference between the initial and final calibration is larger than the experimental error in the evaluation of the peak position were discarded.

During the first cool down, 12 of the 5×5×5 cm^3 and one of the 3×3×6 cm^3 crystals were lost, due to the disconnections at the level of the thermalisation stages which allow the transmission of the electric signals from the detectors to room temperature [40]. Since the active mass was of ∼30 kg, and the energy resolution was excellent, data collection was continued for a few months before warming up the array. The problem has now been fully solved and the detector was cooled down with only 2 of the 13 detectors still disconnected. The data presented here come from the first run and about 3 months of the second run. The total statistics corresponds to an effective exposure of 10.85 kg ×year.

The sum of the spectra of the 5×5×5 cm^3 and 3×3×6 cm^3 crystals in the region of the neutrinoless DBD is shown in Fig. 2. One can clearly see the peaks at 2447 and 2615 keV from the decays of ^{214}Bi and ^{208}Tl, plus a small peak at 2505 keV due to the sum of the two γ lines of ^{60}Co. The background at the energy of neutrinoless DBD is of 0.18 ± 0.01 counts kg^{-1} keV^{-1} y^{-1}.

No evidence is found for a peak at 2529 keV, the energy expected for neutrinoless DBD of ^{130}Te. By applying a maximum likelihood procedure [45, 46], we obtain a 90% C.L. lower limit of 1.8 $\times 10^{24}$ years on the lifetime for this decay. The unified approach of G.I.Feldman and R.D.Cousins [47, 48] leads to a similar result. The upper bounds on the effective mass of the electron neutrino that can be extracted from our result depend strongly on the values adopted for the nuclear matrix elements. As in our previous paper [40] we considered all theoretical calculations [23, 24, 26, 27] apart from those based on the shell model which is not considered as valid for heavy nuclei [49], in particular for DBD of ^{130}Te [27]. We have also not considered the calculation by Rodin et al [50] based on the evaluation of the particle-particle interaction strenght from the corresponding two neutrino DBD lifetime. The evaluation based on single beta decay, which could be preferable [27, 51] is not available for ^{130}Te. The rates for two neutrino DBD of this nucleus based on geochemical experiments are however uncertaint [24, 26, 27]. We have therefore adopted [50] those based on a direct experiment [52].

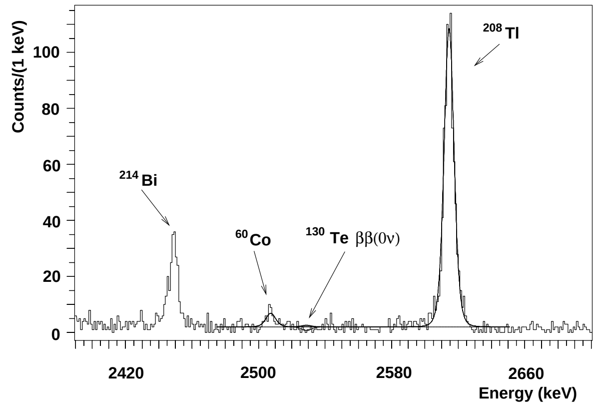

FIG. 2: Spectrum of the sum of the two electron energies in the region of neutrinoless DBD

Taking into account the above mentioned uncertainties, our lower limit leads to a constraint on the effective mass of the electron neutrino ranging from 0.2 to 1.1 eV, and partially covers the mass range of 0.1 to 0.9 eV indicated by H.V. Klapdor-Kleingrothaus et al. [33].

CUORICINO is a first step towards the realization of CUORE (Cryogenic Underground Observatory for Rare Events). It would be an array made by 19 towers, each similar to CUORICINO, with 988 cubic crystals of TeO_2 , 5 cm on a side, and a total active mass of 741 kg. The expected sensitivity on $|\langle m_\nu \rangle|$ of this experiment is of the order of 30 meV, just below the above cited value of 45 meV favoured by current oscillation experiments for the inverted hierarchy. CUORE has already been approved by the Gran Sasso Scientific Committee and by the National Institute of Nuclear Physics (INFN).

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During the run of this experiment in preparing which he so vitally contributed , our colleague Angel Morales , leader of the Zaragoza group, passed away. It was a great loss for science and a great personal loss for all of us.

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